Results of the Ulysses Fast Latitude Scan: Magnetic Field Observations

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ABSTRACT

The rapid crossing of the solar equatorial region by Ulysses as it returned from the south pole resulted in 7 crossings of the heliospheric current sheet between 10“S and 20”N and 10 distinct solar wind interaction regions between 18“S and 22°N. Both the extent of the current sheet and the latitude interval containing the interaction regions are a factor of= 2 less than were observed by Ulysses when it left the equatorial region in 1993. A map of the current sheet in heliographic latitude and Barrington longitude reveals two folds corresponding to 4 magnetic sectors. The coronal holes associated with the sectors, the interaction regions ancl high-speed streams have been identified, Two sectors were associated with a pair of asymmetrically-placed polar coronal holes whereas the other two sectors coincided with a pair of near-equatorial coronal holes on opposite sides of the equator.

A. Introduction

After leaving Jupiter in February 1992, Ulysses gradually traveled inward and southward making continuous observations of the solar wind and magnetic fields. The spacecraft passed below the heliospheric current sheet (HCS) at a latitude of -30° [*Smith et al.*, 1993] and corotating interaction regions (CIRs) essentially disappeared at ≈ -45° [*Balogh et al.*, 1995]. The spacecraft had clearly passed from the low-latitude equatorial region in which fast-slow solar wind streams were interacting strongly into relatively smooth high-speed solar wind flow from the south polar coronal hole *[Phillips et d., 1995].* These general conditions continued as Ulysses left the south polar cap headed for perihelion (at 1.3 AU) and a crossing of the solar equatorial and ecliptic planes. As the spacecraft approached perihelion, it gained speed and passed from moderate to low latitudes very rapidly (at an average angular rate of ~ ½ '/day), a circumstance referred to as the "fast latitude scan" [*Smith et al.,* 1995]. At this phase of the solar cycle, a stable corona is expected with the solar wind being dominated by corotating structures. The rapid traversal of the low latitudes by Ulysses further reduces the possible effect of time variations and the prospects of their masquerading as spatial dependence.

The magnetic field observations which mark this transition to low latitude solar wind are presented here. The spacecraft traversed the equatorial zone in only two solar rotations. Heliospheric current sheet crossings, magnetic sectors and CIRs were once again present. The global structure of the HCS and the origin of the fast streams causing the interaction regions are emphasized.

B. Observations and Analysis

The magnetic field data obtained near the solar equator are shown in Figure 1, a plot of the field magnitude, B, and the field latitude angle, δ, and longitude angle, ϕ, in solar heliospheric coordinates (see caption). The heliographic latitude of the spacecraft is indicated along the upper scale. The field magnitude is steady at the beginning and end of the interval which is centered on the solar equator crossing. These features represent time spent in the high-latitude solar wind. At lower latitudes, large characteristic increases in B are seen that represent interaction regions (IAR) formed at the leading edges of fast streams or ahead of coronal mass ejections (CME).

Ten distinct IARs are observed. All ten appear to be corotating interaction regions (CIRs) accompanying five streams. The five CIRS seen initially are labeled *a* through e. The next five CIRS are are-occurrence of the initial five (based on evidence presented subsequently) and are designated *a'* through e'.

The longitude angle, ϕ, identifies the solar wind sector structure, At the beginning of the pass, $\phi \approx 3\pi/4$ and the field is continuously inward (negative polarity) as it had been for the long duration spent by Ulysses in the south polar region. At the end of the pass, $\phi \approx 7\pi/4$ and the field is continuously outward (positive polarity) as expected for observations in the Sun's northern hemisphere at this phase of the solar cycle. In between, seven distinct changes in polarity, equivalent to seven distinct crossings of the heliospheric current sheet, are evident and are identified by vertical lines and numbers. The first crossing occurred on day 51 at a heliographic latitude of ≈10°S. The last crossing occurred on day *86* at a latitude of ≈20°N. The angular width of the low latitude wind containing the CIRs is only slightly greater than that of the HCS since only a single CIR is seen preceding and following the initial and final crossing of the current sheet.

The field latitude, δ, shows the usual fluctuations about an average value of zero as required by Parker's solar wind model. A large north-south deflection is seen on days 53-55. Features of this kind have often been associated with CMEs, in particular, so-called magnetic clouds. However, this feature does not appear to be a CME based on Ulysses plasma observations *[Gosling et al.,* 1995].

Figure 2 shows the seven crossings as a joint function of heliographic latitude and longitude. The numbers, 1 through 7, show the time sequence of the crossings. The heliographic (Barrington) longitudes were obtained from the sub-solar point of Ulysses as corrected for radial delay (Δr/v). The curve drawn through the points is a cubic spline fit which appears to yield a reasonable representation of the shape. Representation of the current sheet in Barrington longitude makes it possible to compare its structure with other available contours such as those of the source surface neutral line or coronal holes.

The striking feature of Figure 2 is the two folds *or* humps in the current sheet with maxima and minima in latitude at longitudes of ≈0°, ≈100°, =180" and ≈290°. The curve implies that the current sheet has reasonable north-south symmetry both as to its extent and location. The straight lines drawn through points 1-5,6, and 7 represent the subsolar track of the spacecraft. It is apparent that the spacecraft missed the minimum at ≈290° longitude because it was too far south at the time.

The "quadrupolar" current sheet gives rise to four sectors labeled A through D here and in Figure 1. The second traversal of the sectors is designated A' - D'. In general, there is a correspondence between the sector and CIR designations, i.e., C - c, D - *d,* etc.

The hemispheric origin of the streams responsible for the CIRS can generally be inferred from their magnetic polarities with positive streams coming from the north and negative streams from the south, Whenever a CIR contains the current sheet, the trailing polarity in time is the polarity of the associated fast stream. Thus, a +/- crossing implies the CIR is caused by a negative (southern) stream whereas a -/+ crossing implies that the accompanying stream is from the north.

Figure 3 shows the HCS fit with the addition of symbols (arrows) indicating whether fast streams are from the north or south. Streams associated with the ten CIRs are shown in time sequence, *a - e* and *a' - e'* corresponding to Figure 1. The arrows are placed at the subsolar points at which maximum B was observed in each CIR. Initially, the arrows along the upper track were labeled *f* through *j*, until further analysis established which arrows were related to (hose along the lower track and this correspondence was then expressed through the use of primes.

The positions of the arrows are influenced by the choice of the longitude system. The Barrington longitudes assume a solar rotation period of 27 days, the synodic period as observed at Earth. Ul ysses, however, is traveling south-north at high inclination and, as indicated in Figure 1, the recurrence period of the CIRs is ≈ 25 days nearly corresponding to the sidereal solar period of 25.4 days. The more rapid rotation of the CIRS will cause them to advance (increase) in Barrington longitude ≈ 25° per rotation. The displacements of *a - a'*, *c - c'* and e - e' are qualitatively consistent with this effect but are significantly larger, typically ≈ 50°, Furthermore, *d- d'* do not follow this pattern. We believe the principal cause for these non-alignments is the geometry of the CIRS which tend to follow the HCS rather than being oriented north-south (see Discussion).

The correspondence between the direction of the arrows and the current sheet folds is generally what would be expected. Northward displacement of the HCS is associated with streams from the south (b, *d* also *b', d')*. Southward displacement is associated with streams from the north (c, e also c', e'). The stream responsible for *a* is an exception. CIR-*a* is not accompanied or followed by a current sheet crossing. This ambiguity is discussed below.

C. Discussion

The unique trajectory of Ulysses has provided an excellent map of the HCS near sunspot minimum. [*Villante et al.*, 1979] used simultaneous Helios 1,2 observations over four solar rotations (Jan-May 1976) to prepare a similar map which was consistent with a warped current sheet inclined ≈10° to the heliographic equator. In Figure 2, the seven crossings have been used to convey the HCS structure. The dominant features are the two folds and four sectors, The occurrence of four sectors near sunspot minimum is not surprising because the current sheet inclination is typically low. The latitudinal extent of the current sheet north and south is a rough measure of its inclination to the solar equator. During the fast latitude scan, this pseudo-inclination is only ≈ 15". In April 1993, Ulysses passed below the HCS at -30° which shows that the inclination has decreased by a factor of ≈ 2 as solar minimum approaches.

The Ulysses map provides a further opportunity to test the various source surface models of the solar wind magnetic field, One of the Stanford University models readily available electronically (courtesy of T. Hoeksema) also shows four maxima-mi nima at nearly the same longitudes as Figure 2. However, the model also includes a slight southward displacement of the current sheet with minima and maxima at 10"S and 5"N which is not confirmed by the observations. Further, more detailed comparisons are called for.

In addition to the current sheet crossings, ten CIRs were observed. Figures 3 shows that, although the HCS has two peaks and two valleys, more than the minimum number of four streams, two in the north and two in the south, were present. Figure *3* shows that c - c', e - e' originate with northern streams and *b - b', d - d'* with southern streams. As noted above, the association of *a* with *a' is* ambiguous. The arrow at *a* indicates an association with *a* that is based on the following discussion.

The ambiguity can be resolved by noting the recurrence of *a* as a' which lies in positive sector, A, and the location of the HCS which is north of *a*. A likely explanation is that the stream responsible for *a'* also caused CIR - *a* to form below the current sheet. CIRS *a* and *a'* are probably not connected topologically but represent a pair of CIRs associated with a stream from the north. This unusual configuration may be a consequence of having two fast streams in a single sector. Thus, we conclude that two streams, *a - u', e - e'*, occupy sector A and that there are three streams from the north and only two from the south.

It is not unusual for a sector to contain two fast streams, however, attention to this kind of detail is important in relating streams to coronal holes (or other solar wind structures) and in understanding the formation of CIRs.

Near solar minimum, fast streams are expected to come from coronal holes. We have attempted to identify streams and magnetic sectors with coronal holes using the readily available 1083 nm maps provided by the National Solar Observatory at Kitt Peak [*Solar Geophysical Data*, 1995]. The results are shown in Figure 4 which contains four coronal hole images which we associate with the four sectors. We converted the Barrington longitudes of the CIRs ancl sectors into the equivalent times and inspected the coronal hole plots day-by-day looking for the expected correspondences. Thus, we associate sector A (+) with the north polar coronal hole (PCH) seen on 19 February, sector B(-) with the PCH seen on 25 March and sectors C (+) and D (-) with the pair of equatorial coronal holes (ECH) *seen* simultaneously on 4 March and again on 31 March. Figure 4a actually shows two coronal holes in the northern hemisphere, a PC} I and a detached mid-latitude hole lying below it and to one side. This configuration may explain the two streams in sector A.

Figure 3 can also be compared with 3D solar wind models which include a tilted current sheet and a latitude gradient in solar wind speed, e.g., [*Pizzo,* 1994]. The separation between the first and last CIR and the first and last HCS crossing indicate the width of the band of slow wind surrounding the HCS. Thus, the current sheet crossings extend over a latitude range of ≈ 30° while the CIRS cover ≈ 40" in latitude. Evidently, the transitions between high-speed high-latitude wind and low-speed low-latitude wind took place in only a few degrees. Furthermore, this width has changed considerably since 1993. After the last HCS crossing at ≈ 30°S, CIRs continued to be present until ≈ 45"S. Thus, both the current sheet and band of slow wind have shrunken in latitude by ≈ 2 in the intervening 2 years.

A characteristic feature of the 3D model is that the solar wind velocity contours are parallel to the HCS. The interfaces trail the current sheet and slope upward in latitude-longitude for crossings from below *to* above the HCS. Conversely, they slope downward for crossings from above to below the current sheet. An interesting aspect of Figure 3 is the presence of this tendency. CIRS ***d*** and *d'* show a downward slope while c - c' and *e* - e' imply an upward slope of the interfaces as anticipated. The relation between *b - b'* and *a - a'* does not follow this simple rule, the latter presumably for the reasons discussed above.

Ulysses is now traveling northward having reached the edge of the polar cap (defined as 70°N) on 19 June 1995. It will be interesting scientifically to compare the high latitude wind from the north and south hemispheres. After 30 September 1995, the spacecraft will execute another slow latitude scan of the north hemisphere concluding in April 1998 at a distance of 5.4 AU.

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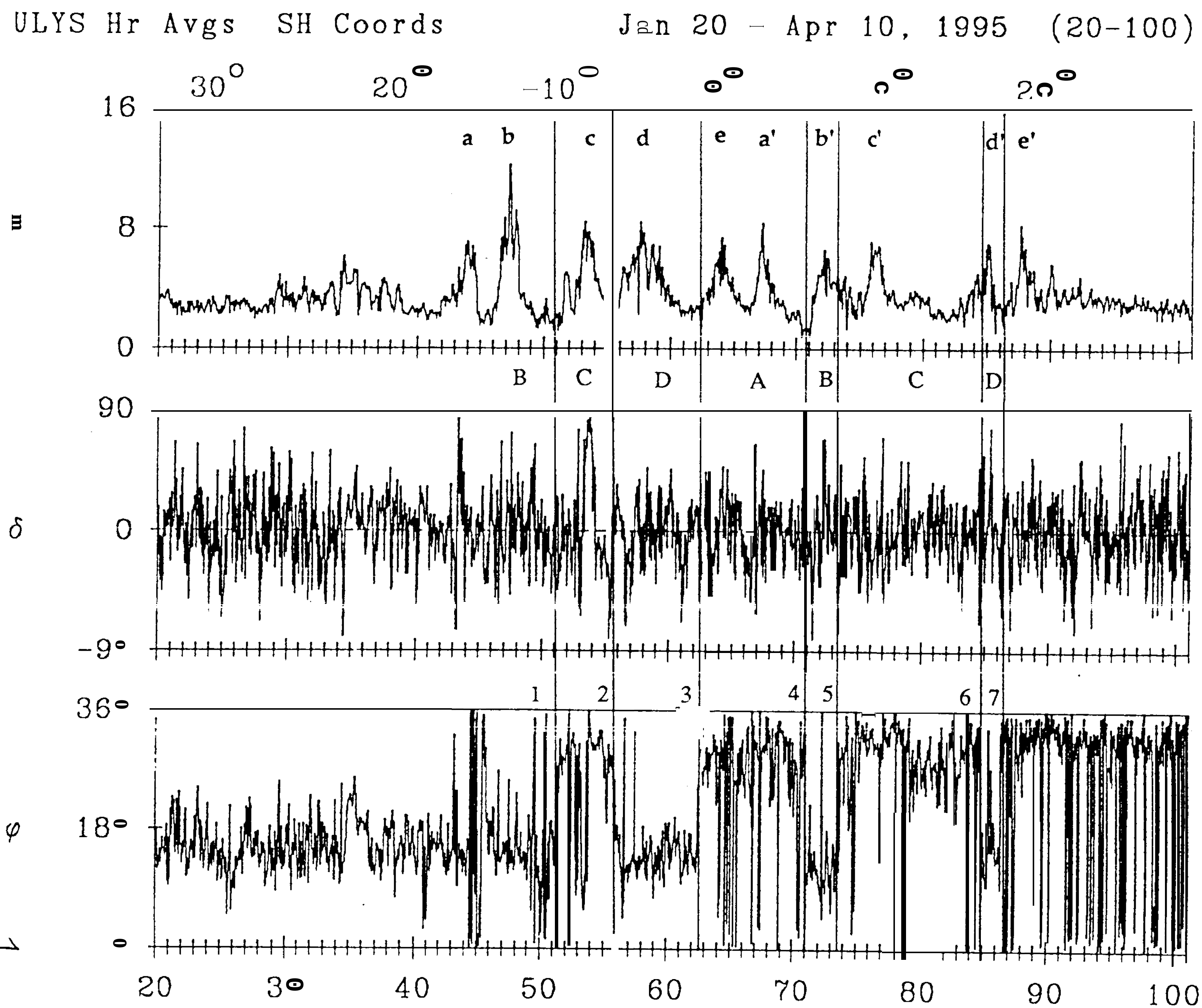
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20°
-10°
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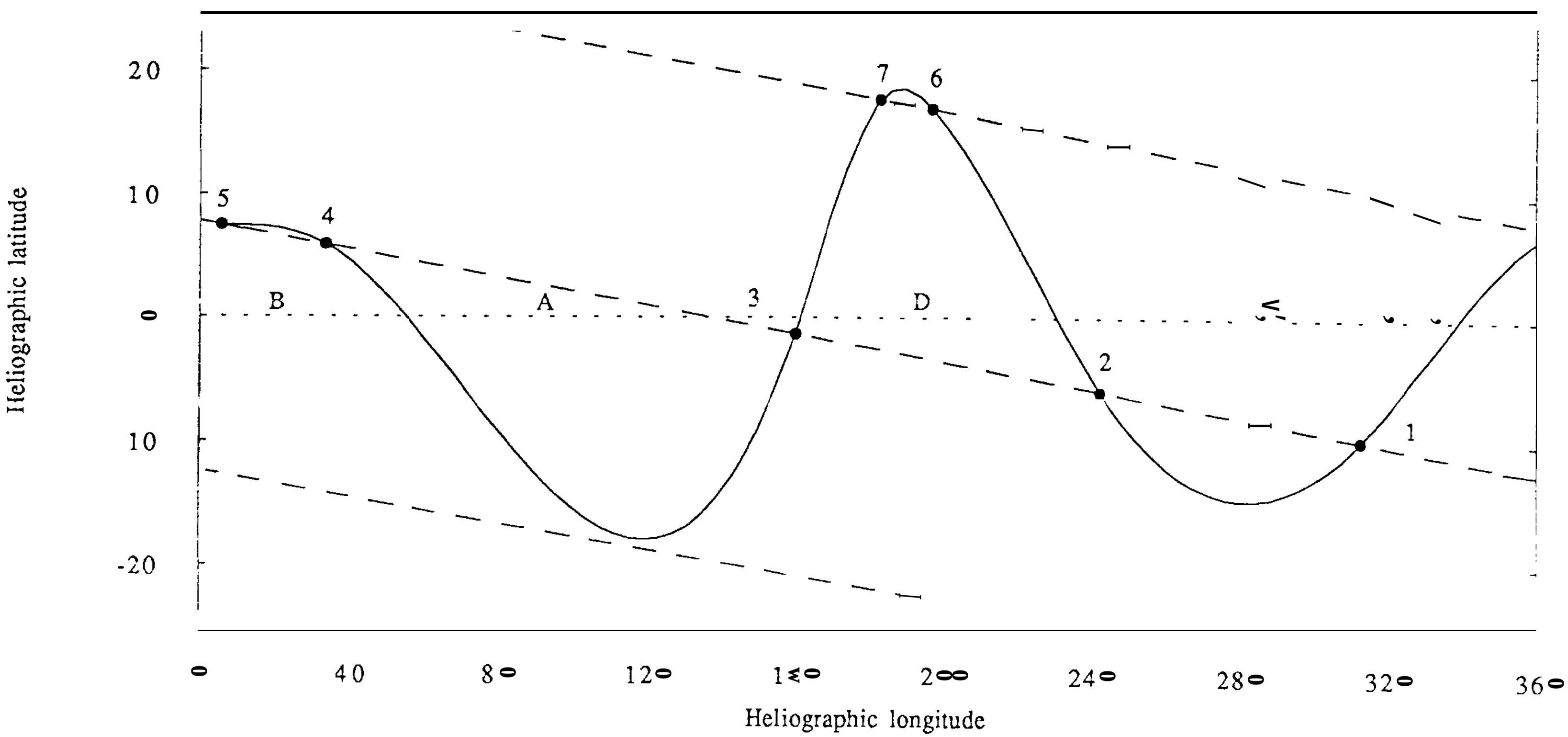

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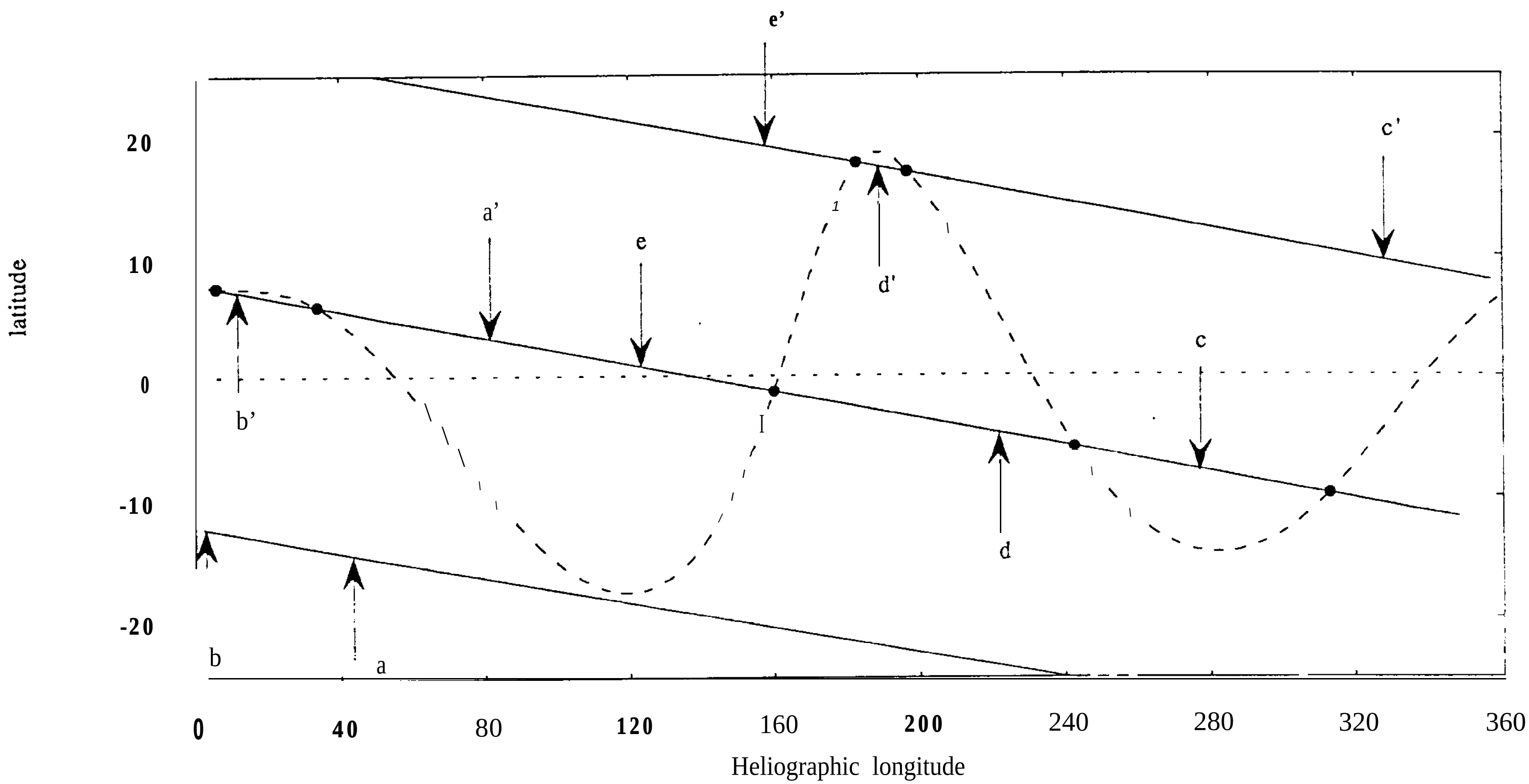

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3

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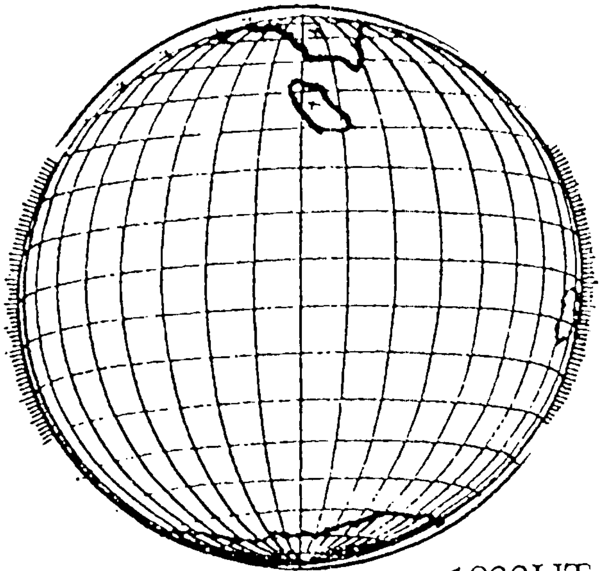

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B

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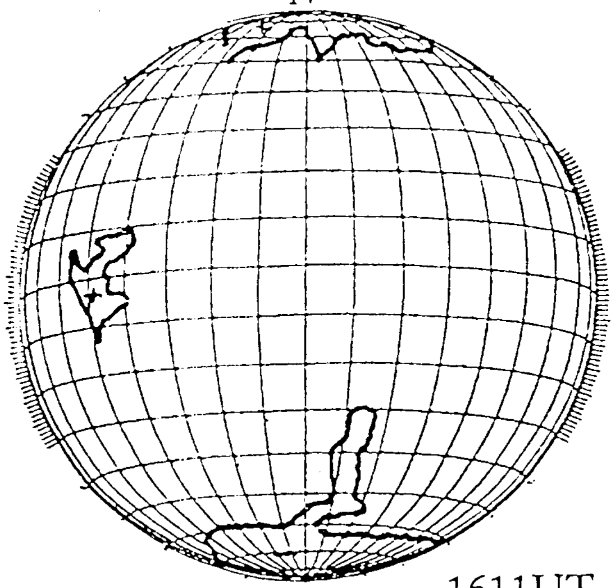

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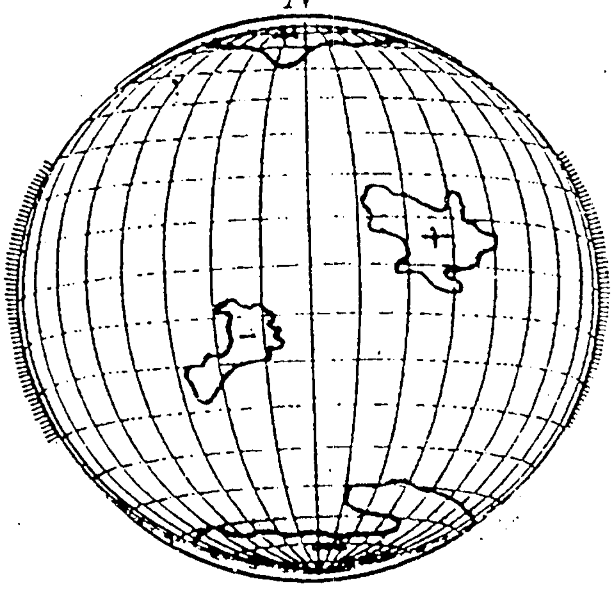
N



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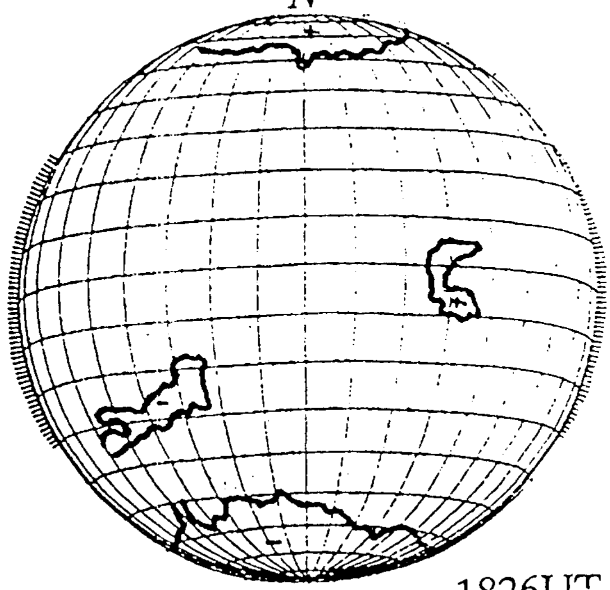
D C

N



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D' C'

4.